# REPORT FROM THE TECHA RIVER DOSIMETRY REVIEW WORKSHOP HELD ON 8–10 DECEMBER 2003 AT THE STATE RESEARCH CENTRE INSTITUTE OF BIOPHYSICS, MOSCOW, RUSSIA

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***Abstract*—Large releases of fission products into the Techa River, in the Southern Urals, occurred in 1950 and 1951, during the early years of operation of the Mayak Production Association (Mayak PA), which produced plutonium for nuclear weapons. Increases of leukemia and of solid cancers with radiation dose have been noted in the population of about 30,000 people who lived in the settlements downstream of the site of the radioactive releases; that population has been studied for several decades by Russian scientists, notably in the framework of cooperation with American and European scientists. The radiation doses are currently estimated by means of the Techa River Dosimetry System-2000 (TRDS-2000). Recently, a scientist from Mayak PA has suggested in several publications that the doses calculated using TRDS-2000 might be underestimated substantially. A special international Workshop, held in Moscow on 8–10 December 2003, aimed to resolve some of the pressing issues related to the determination of the external and internal doses received by the Techa River population and to give recommendations on the further development of methodologies used for dose reconstruction. The authors of this article were selected by the organizers of the Workshop to draw the conclusions of the meeting. They express the view that, while the dose reconstruction system TRDS-2000 is basically sound, additional work is needed and the results of any epidemiological studies making use of TRDS-2000 should be qualified as preliminary, pending resolution of several issues. The most important of these issues is the re-evaluation of the activities released, using additional information that could be obtained with the help of Mayak experts. Other specific suggestions aiming to improve the dose reconstruction methodology for the Techa River cohort, i.e., continued measurements of accumulated dose in environmental samples and human tissues, validation of external dose estimates with thermoluminescence measurements of bricks and with electron paramagnetic resonance measurements of teeth, estimation of individual doses instead of group doses, detailed account of the contributions to dose of medical examinations and of other releases from the Mayak complex, and careful assessment of the uncertainties, were made by the meeting participants.**

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**Key words: health effects; dose assessment; contamination, environmental; modeling, dose assessment**

## BACKGROUND

### History of Mayak operations and associated radioactive releases

The Mayak Production Association (Mayak PA) was created in 1948 in the Southern Urals for the production of plutonium for nuclear weapons. During full power operation, this complex consisted of (1) six graphite-moderated reactors using direct flow water-cooling loops and one heavy-water moderated reactor operating with thermal neutrons; (2) a radiochemical plant for the extraction of $^{239}$Pu from uranium irradiated in the reactors; (3) a chemical-metallurgical plant for metallic plutonium production and machining; and (4) facilities for radioactive waste management and storage. The graphite-moderated reactors have now been shut down; the heavy-water reactor, which has been modified to become a light-water moderated reactor, remains in operation today for the production of isotopes for civilian uses. Since 1977, the radiochemical plant has been used extensively to reprocess fuel from power, transport, and research reactors.

The extensive increase in plutonium production during the 1948–1955 time period, as well as the absence of reliable waste-management technology, resulted in significant releases of radioactive materials into the environment and in the contamination of surrounding territories. The major sources of environmental radioactive contamination were (1) the discharges of medium

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level liquid radioactive wastes into the Techa River (1949–1956); (2) an explosion in 1957 in the radioactive waste-storage facility (the so-called Kyshtym accident) that resulted in the dispersion of 74 PBq of radioactive materials into the atmosphere and in the formation of the East Urals Radioactive Trace (EURT); and (3) gaseous aerosol releases (about 20 PBq of $^{131}$I in total) within the first decades of the facility's operation. A substantial fraction of the activity released into the Techa River and deposited in the EURT consists of long-lived radionuclides, mainly $^{90}$Sr and $^{137}$Cs.

The largest releases of radioactive materials into the Techa River occurred in 1950 and 1951 (Fig. 1), when one to three graphite-moderated reactors were in operation. During that period of time, the release rates amounted to about 150 TBq d$^{-1}$, although they were widely variable from one day to the next (Table 1) and their estimates are associated with considerable uncertainty. In late 1951, several procedures were implemented to control the releases and to remediate the environmental contamination. The main liquid technological releases were diverted from the Techa River into Lake Karachay. A series of dams were built on the upper Techa River with bypass canals to halt the spread of contamination. About 7,500 people from the contaminated villages were resettled in uncontaminated areas between 1955 and 1960.

## Studies of health effects among the residents of the Techa River basin

The residents of the communities along the Techa River were exposed to external gamma irradiation from the contaminated river shore and flood plains and to internal irradiation from radionuclides ingested mainly

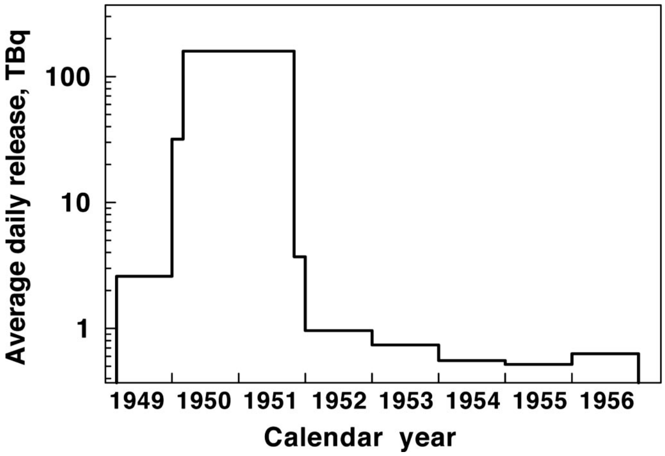


**Fig. 1.** Average daily releases of radioactive materials into the Techa River during the 1949–1956 time period (according to Ilyin 1956; Marey 1959).

**Table 1.** Releases into the Techa River during September–October 1951 (modified from Alexandrov et al. 1951).

| Date | Volume ($m^3$) | Concentration (GBq $m^{-3}$) | Daily release (TBq) |
|---|---|---|---|
| 25.09 | 8,350 | 40 | 340 |
| 26.09 | 8,350 | 26 | 220 |
| 27.09 | 8,100 | 380 | 3,100[a] |
| 28.09 | 8,300 | 330 | 2,800[a] |
| 29.09 | 8,125 | 130 | 1,000[a] |
| 30.09 | 7,850 | 22 | 170 |
| 01.10 | 7,850 | 3.3 | 26 |
| 02.10 | 8,070 | 37 | 300 |
| 03.10 | 8,090 | 3.7 | 30 |
| 04.10 | 8,900 | 8.1 | 72 |
| 05.10 | 8,600 | 20 | 170 |
| 06.10 | 9,200 | 13 | 120 |
| 07.10 | 8,800 | 13 | 110 |

[a] The daily releases that are reported for 27–29 September include unintended releases.

with river water. The "Extended Techa River Cohort" (ETRC), which consists of about 30,000 persons who lived in the settlements downstream from the site of liquid radioactive releases, has been studied for several decades by scientists from the Urals Research Center for Radiation Medicine (URCRM) and from the Moscow Institute of Biophysics (IBPh). Early deterministic health effects, i.e., cases of chronic radiation syndrome, were registered among residents of the upper Techa area (Kossenko et al. 1994). Subsequent increases in both leukemia and solid cancers with radiation dose have been noted for this cohort (Kossenko et al. 1997, 2002).

The persons born to exposed subjects of the ETRC since 1950 form the "Techa River Offspring Cohort" (TROC). Radiation factors that may have exerted an influence on the progeny include exposure of parental gonads before conception, exposure during the in utero period of gestation, and exposure during the postnatal period. The study of the members of the TROC has the potential to provide useful information on health effects in the progeny of a relatively large population that was exposed to chronic radiation.

In order to quantify the radiation risks per unit dose in the conditions of chronic exposure for the general public, as well as to validate threshold doses for deterministic effects under those conditions, it is very important to provide reliable individual dose assessments for members of the ETRC and of the TROC. Therefore, since the very beginning of the health-effects studies, intensive efforts have been devoted to the reconstruction of doses (Degteva et al. 1996). Studies of the possible effects of radiation among the populations exposed to the releases to the Techa River, as well as an extensive environmental monitoring program, were started in Russia in 1951, at the end of the large release period. The information collected for several decades has been accumulated at the URCRM and has been entered into databases containing original data for dose reconstruction and risk assessment studies. Unfortunately, the absence of monitoring data before 1951 increases the uncertainty of the dose estimates, which are based partially on indirect environmental data.

The Techa River studies have been internationally recognized to be of potentially large importance for radiation medicine and for radiation protection of the public. Since the 1990's, they have been substantially supported by the U.S. Department of Energy (DOE) and, to a lesser extent, by the European Commission (EC) and the U.S. National Cancer Institute (NCI).

Since 1995, Russian and American scientists have been involved in a collaborative research program under the auspices of the Russian–U.S. Joint Coordinating Committee for Radiation Effects Research (JCCRER). JCCRER Project 1.1 "Techa River Population Dosimetry" is a comprehensive project to develop improvements in the dosimetry system for members of the ETRC by providing more in-depth analysis of existing data, further search of existing records, model development and testing, evaluation of uncertainties, and validation studies of results. The purpose of the enhanced dose reconstruction is to support epidemiological studies of radiogenic leukemia and solid cancers (NCI-RERF-URCRM Project and JCCRER Project 1.2b "Techa River Population Morbidity"). Many improvements were accomplished recently in the derivation and implementation of the Techa River Dosimetry System-2000 (TRDS-2000; Degteva et al. 2000a, b); these improvements resulted in major changes in the estimates of external dose. Validation of the new external dose estimates is considered to be a critical factor for the credibility of the TRDS-2000 results and of the epidemiological studies that they support.

Work on the validation of the external dose estimates is being performed in close cooperation with scientists from various European research institutes and is being supported by the European Commission. In these projects, solid-state dosimetry methods (luminescence in bricks and electron paramagnetic resonance with human teeth) and biodosimetric methods (fluorescence in-situ hybridization of lymphocytes) have been used for the validation of the TRDS-2000 external dose estimates. Another aspect of the collaboration with European scientists is an epidemiological investigation of the Techa River Offspring Cohort (TROC). Individual dose estimates for all TROC members, based on the TRDS-2000 approach, are used in the analysis of possible health effects in the progeny of exposed people.

The preliminary leukemia and solid cancer radiation risk coefficient estimates for the ETRC cohort were presented informally at an international workshop held in Bavaria in June 2002 (Workshop 2002). These preliminary estimates were based on the recently released TRDS-2000 dosimetry data and on the most recent cancer mortality follow-up. Surprisingly, these risk coefficients for persons exposed to chronic radiation were substantially higher than those obtained for the acute exposures of the Japanese A-bomb survivors (Preston et al. 2003). This is unexpected since much of the radiobiological experience indicates that chronic low-LET radiation is 2 to 10 times less effective than acute radiation with regard to stochastic effects in mammals (NCRP 1980); for humans, it has been suggested that risk estimates derived from acute exposures should be divided by a factor of 2 for chronic exposures (UNSCEAR 2000).

Possible explanations of these surprising results were advanced at the meeting in Bavaria and afterwards, including the large uncertainties of the risk estimates for the ETRC members, the possibility of abscopal effects, and the underestimation of the doses for the ETRC population (Kellerer 2002). The simplest explanation would be the underestimation of the doses for the ERTC population. If the true doses were higher than those predicted by TRDS-2000, then the risk coefficients would be proportionally lower and compatible with those estimated for the A-bomb survivors.

A Mayak PA staff member, Yuri Mokrov, has recently published a series of papers, both in Russian and in western journals, suggesting that substantial corrections to the existing TRDS-2000 may be warranted (Mokrov 2002a, 2002b, 2003a, 2003b, 2003c, 2004). These suggestions are based on a re-evaluation of the historical radiation monitoring data and on the use of different radioecological models, resulting in changes in the amounts of radioactive materials released from the plant and in the extent to which the Techa River and associated water bodies were contaminated (Mokrov 2003a, 2003b). Because Mokrov's findings may result in substantial increases in the dose estimates for the Techa River residents, and, in turn, in changes in the risk estimates (Kellerer 2002), the need to discuss openly the emerging contradictions was recognized.

During the meeting in Bavaria, it also was pointed out that the TRDS-2000 methodology considers only the discharges of radioactive waste into the Techa River and does not take into account other sources of radiation exposure that may not impact the ETRC members in a uniform manner. The sources of exposure that are not accounted for in the TRDS-2000 methodology include:

- the airborne emissions from the Mayak PA stacks (primarily $^{131}$I and rare gases);
- the airborne radionuclide releases from the Kyshtym accident in 1957;
- the resuspension of radioactive aerosols from Lake Karachay in 1967; and
- the medical exposures due to the intense surveillance of the ERTC members.

## OBJECTIVES OF THE WORKSHOP

An open discussion between the interested research groups and with the participation of impartial international experts had become important in order to ensure that the risk estimates that will be derived from the Techa River cohort morbidity and mortality studies will be endorsed by the international community. Therefore, the U.S. Department of Energy (DOE), in conjunction with the Russian Ministry of Health, the U.S. National Cancer Institute (NCI), and the European Commission, decided to convene a Workshop to resolve some of the pressing issues on how best to characterize the dose estimates available for the Techa River population. The Workshop was held on 8–10 December 2003, at the State Research Centre Institute of Biophysics, Moscow, Russia; its participants included not only the principal Russian, U.S., and European investigators of the research projects directly relevant to the Techa River radiation-induced health studies, especially with regard to its dose reconstruction issues, but also a number of other Russian, European, and U.S. experts with substantial experience in similar studies. A list of participants in the Workshop is provided in the Acknowledgements.

The specific goals of the Workshop were to review and discuss issues related to external and internal dosimetry for the Techa River cohort and to give recommendations on the further development of methodologies to be used for its dose reconstruction.

Both the discussions held in the Workshop and recently published papers on its topic are summarized in this article, which is based on the main conclusions that have been broadly agreed upon by the Workshop participants. The authors of this article are four scientists—two from the Russian Federation, one from Sweden, and one from the United States—who are not directly involved in the JCCRER Techa River studies and who, prior to the Workshop, had been selected by the organizers to draw the conclusions of the meeting.

The consensus was reached in the following way. The draft paper was first prepared by its four impartial authors and distributed to the meeting organizers representing the U.S. Department of Energy, the Russian Ministry of Health, the European Commission, and the U.S. National Cancer Institute. It was *a priori* agreed that the report would be submitted for publication only if a consensus could be reached between its four impartial authors and the four meeting organizers supported by their respective experts. All addressees of the draft report had numerous opportunities to provide their comments and to suggest modifications, including the addition of relevant materials. As many of the discussion participants expressed different views on the Techa River dose reconstruction methodology, input data and results, it took about half a year and at least five paper circulations before a consensus was reached in September 2004.

## GENERAL APPROACH TO HUMAN DOSE RECONSTRUCTION

### Sources and pathways of exposure

For the populations living along the Techa River, the predominant source of exposure was the discharge of radioactive wastes into that river. The wastes consisted of radionuclides that were soluble in water and of radionuclides that were attached to particles. As the wastes moved downstream, the more insoluble radionuclides became attached to sediments; during periods of flooding, radionuclides were also deposited on flood-plain soils.

The two dominant pathways of exposure related to the discharge of radioactive wastes into the Techa River were (1) external irradiation due to the emission of gamma rays from the radionuclides deposited along the shore and on flood-plain soil, and (2) internal irradiation arising from the ingestion of contaminated water and foodstuffs. The dose from external irradiation was relatively more important for the populations residing on the upper reaches of the river because of the rapid attachment of radionuclides to sediments. The dose from external irradiation was highly variable and depended upon many factors, including the length of time spent near the shore and the distance of the residence from the river shore. With regard to internal irradiation, the most important source of exposure was usually the ingestion of contaminated drinking water for residents who used the river as a source of drinking water. In addition, foodstuffs became contaminated because of the use of contaminated flood plains for pasturing or for crop growth, and, also, in some cases, because of irrigation with river water.

Although the predominant source of exposure was the discharge of radioactive wastes into the Techa River for the populations living along that river, other sources may need to be taken into account. Sources of exposure related to environmental radiation include the airborne emissions (primarily $^{131}I$ and rare gases) due to routine releases from the Mayak PA stacks, the airborne emissions from the 1957 explosion (particularly for some residents who were evacuated to locations contaminated by those emissions), and resuspension of aerosols from Lake Karachay after the lake receded in the 1960's and the old shore line dried out. These sources of exposure are being evaluated for inclusion into the overall assessment of dose to the members of the ETRC. In this regard, studies related to the assessment of doses to the public resulting from airborne releases from Mayak PA during the first years of its operation have been initiated recently within the framework of JCCRER Project 1.4 "Reconstruction of Dose to Residents of Ozersk from the Operation of the Mayak Production Association."

In addition, the persons living along the Techa River who were believed to be highly exposed to the releases were subjected to intense medical surveillance, which included radiological examinations. This additional source of exposure is also evaluated.

## Available monitoring data

The monitoring data related to the environment and to the concentrations of radioactive materials in the human body are considered separately.

**Environmental monitoring data.** Systematic measurements of radioactive contamination in and near the Techa River started in July 1951, about half a year before the end of the 2-y period of large releases. The contamination of the river water, bottom sediments, flood-plain soils, vegetation, fish, milk, and other foodstuffs, as well as exposure rates on the river banks and on the flood-plain soils, were measured. There were no environmental radiation measurements before July 1951; this represents a major source of uncertainty in the dose reconstruction studies related to the Techa River populations.

In the 1990's, historical data of importance for dose-reconstruction purposes were collected and organized in the special computer database ENVIRONMENT at the URCRM. This database now includes more than 10,000 records of environmental radiation measurements for the period 1951–1990: total alpha, beta, and gamma activities in many types of environmental samples; concentrations of $^{90}Sr$ and $^{137}Cs$ in river water; concentrations of $^{90}Sr$ and $^{137}Cs$ in bottom sediments and flood-plain soils; and exposure rate measurements. The most extensive data set is on beta activity of the Techa River water. The numbers of measurements of gamma- and alpha-emitter concentrations in river water are small in comparison with those of beta activity. A limited number of radiochemical analyses of river water also were made in 1951–1956, but the results are incomplete and sometimes discrepant.

The first measurements of exposure rate were performed in 1951 at several specific sites in the upper reaches of the Techa River. Starting in 1952, such measurements were performed along the entire Techa River. The exposure rate at a particular location did not change significantly from 1952 to 1956; this is a rather strong indication that during that period of time the main contributors to the external dose were long-lived radionuclides (presumably primarily $^{137}Cs$). Exposure rates measured at various distances from the shoreline at several sites suggested that the main source of gamma radiation was the contaminated silt, with no appreciable shielding by the water layer near the river bank.

The analysis of the available historical monitoring data indicates that the following reliable data sets can be used for the reconstruction of doses received during the early periods of operation of the Mayak PA:

- the temporal pattern of the beta activity of the river water for several sites in the upper reaches of the Techa River since July 1951;
- the average annual values of beta activity of the river water and of the bottom sediments as a function of downstream distance for the whole river since 1951;
- the measurements of exposure rate near the shoreline as a function of downstream distance for the whole Techa River since 1952; and
- the measurements of exposure rate as a function of distance from the shoreline for several sites in the upper and middle Techa River since 1951.

The data described above are available in the following documents: the A.P. Alexandrov's Commission Report (Alexandrov et al. 1951), Mayak PA Technical Reports (Ilyin et al. 1951a, 1951b, 1952, 1953; Lemberg and Antipina 1951; Ermolaev et al. 1952, 1955), Institute of Biophysics Technical Reports (Marey et al. 1952, 1953, 1954, 1956, 1965; Alekseeva et al. 1957; Anikin et al. 1959; Borovinskikh et al. 1958), URCRM Technical Reports (Dubrovina et al. 1961; Sarapultsev 1966; Antropova et al. 1971, 1978; Panteleev et al. 1971; Shuhovtsev et al. 1978; Safronova 1981; Safronova and Skryabin 1983; Kozheurov 1985; Safronova et al. 1986; Goloschapov et al. 1990), D. I. Ilyin's Doctoral Thesis (Ilyin 1956), A. N. Marey's Doctoral Thesis (Marey 1959), and M. M. Saurov's Doctoral Thesis (Saurov 1968).

**Data on radioactive materials in the human body.** Systematic measurements of radionuclide concentration in bioassay and autopsy samples were started in July

1951. The autopsy program continued up to 1993, and about 10,000 measurements of $^{90}Sr$ concentration in bones and teeth were performed. Since 1959, in vivo measurements of surface beta activity on the front teeth have been performed using tooth-beta counters: 12,000 persons were investigated during the 1959–1997 time period. In addition, since 1974, the residents of the Techa River basin and nearby territories have been examined for their $^{90}Sr$ and $^{137}Cs$ body burdens with a whole-body counter (WBC) that was specially designed for this study; from 1974 to 1997, a total of 20,000 persons were measured using the WBC. These data are very important for the reconstruction of internal doses caused by ingestion of long-lived radionuclides.

### Methodologies of retrospective dose assessment

Radiation dose reconstructions are generally based on the analysis of the different steps of the pathway of exposure to man, which are, for example: release $\rightarrow$ atmospheric transport $\rightarrow$ deposition on the ground $\rightarrow$ intake/exposure $\rightarrow$ dose, in case of a release into the atmosphere (ICRU 2002). Radioactive materials released to the environment generally are transported, deposited, and taken up in plants and animals in ways that are independent of individual humans. Individuals are exposed to time-varying "fields" of radiation and radioactive materials. Therefore, it is possible to reconstruct the time histories of the radiation fields and radionuclide concentrations in the environment without considering the dietary and lifestyle habits of specific individuals. Once the time histories of the radionuclide fields throughout an area are known, it is possible to "introduce" the people into them and to estimate the intakes of the considered radionuclides by humans and the resulting doses. The individual dose calculation requires individual-specific information that must be obtained from the individual that is considered.

For the Techa River exposure situation, historical information on the Mayak releases in 1949–1951 is limited. Historical environmental monitoring data in the areas where the ETRC members resided are only available since 1951. However, measurements of radionuclides in specific people ($^{90}Sr$ in whole-body, bones or teeth, etc.) are available for about half of the ETRC members and may be used to estimate their individual internal doses caused by intakes of $^{90}Sr$ and $^{137}Cs$ and, by inference, by intakes of other radionuclides. The dose reconstruction process used in TRDS-2000 is based extensively on the measurements of external exposure performed directly in the places where people lived and on measurements of radionuclide burden in humans. The traditional way of analyzing all steps of the pathway of exposure is only used as a backup when other approaches have been exhausted. In the following sections, the data, assumptions, and models used in the TRDS-2000 dosimetry system and in Mokrov's recent findings are presented in turn.

## SOURCE TERM

In this paper, the source term refers to the activities released into the Techa River and to their radionuclide composition.

### TRDS-2000 dosimetry system

There were two major sources of radioactive releases into the Techa River in 1950–1951: "normal discharges"—liquid wastes from the process of extracting $^{239}Pu$ from irradiated uranium blocks at the radiochemical plant, and "unintended releases"—episodic leaks of high-level wastes washed by cooling water from tanks of the waste-management and storage facility. The daily releases reported for the time period from 25 September to 7 October 1951 are presented in Table 1 (Alexandrov et al. 1951). The large values reported for 27–29 September are presumably due, mostly, to unintended releases, while values for the other days are attributed to normal discharges. Excluding the daily releases reported for 27–29 September, the average daily release is about 150 TBq $d^{-1}$. The relative contributions of the "normal discharges" and of the "unintended releases" to the total releases in 1950–1951 are unknown.

The total activity of fission products released into the Techa River was estimated by the Mayak expert D. Ilyin (1956) and confirmed later by other Mayak experts (JNREG 1997; Mokrov et al. 2000) to be about 100 PBq (2.8 MCi) of beta emitters.

The publicly available information on the radionuclide composition of the releases for the 1949–1951 time period has been extracted from only two archival sources of primary data: (1) D. Ilyin's doctoral thesis (1956) based on an evaluation of the release data that were available in the early 1950's, and (2) the report of the A.P. Alexandrov's Commission (1951) in which the results of the only radiochemical measurement of the release water, on a sample taken on 24–25 September 1951, are presented. The measured radionuclide composition in that sample was different from Ilyin's evaluation. In TRDS-2000, it is assumed that the releases of radioactive wastes into the Techa River consisted of a mixture of materials from various stages of processing, with a radionuclide composition corresponding to an average age of fission products of 1 y (Vorobiova et al. 1999). This source term was used in TRDS-2000 for Techa River modeling and external dose reconstruction for 1950–1951 as well as for internal dose reconstruction due to short-lived radionuclides for 1950–1952.

**Recent findings**

The results of the radiochemical analysis of the release water sample from 24–25 September 1951 (Alexandrov et al. 1951), corresponding presumably to normal discharges, have been recently re-interpreted by Mokrov (2003a, 2003b). Mokrov accounted for the energy-dependent absorption of beta radiation in the end-window counter window material and suggested the use of a correction factor of 1.4 to 1.7 for the sample's total beta activity assuming a hold-up time of unseparated mixture of fission products in the range from 10 to 365 d. He used the available 5-group radiochemical distribution of the total beta activity and measured $\beta/\gamma$ ratios in order to specify the hold-up time of the irradiated fuel. Based on these two criteria applied to the single sample that is available and on a memoirs publication (Kruglov 1995), Mokrov suggested that a radionuclide composition of the normal discharges corresponding to a fuel irradiation time of 120 d and a hold-up time of 35 d was more appropriate for dose reconstruction than the radionuclide composition corresponding to an average age of fission products released to the Techa River in 1950–1951 of about 1 y that is used in the existing TRDS-2000, on the basis of a previous Mayak PA analysis.

With regard to unintended releases, Mokrov (2003a) estimated tentatively that the radionuclide composition in the high-level waste tanks at the time of the leaks would correspond to a filling time of 120 d.

The implications of Mokrov's re-interpretation are that releases of $^{90}$Sr and $^{137}$Cs into the Techa River in 1949–1951 would be about 1 PBq for each of these nuclides, which is about an order of magnitude lower than earlier Mayak PA estimates. In contrast, the total released activity of about 100 PBq would be an underestimate, and the real total release would be several times higher. The overall result would be a greatly increased ratio of short-lived to long-lived radionuclides.

**Analysis**

At least two types of radioactive releases into the Techa River occurred in the 1949–1951 time period. The so-called normal discharges apparently were neutralized liquid radioactive wastes (LRW) coming directly from the separation process with only a small time delay before release. Another type of discharge (so-called unintended discharges) was due to leaks from stirred high-level waste (HLW) tanks containing acidic HLW. Both types of release probably also contained suspended solids in addition to the liquid. The continuous filling of the HLW tanks makes it reasonable to assume that the release from this source still contained some radionuclides with intermediate half-lives. The delay between fuel unloading from the reactor and the corresponding normal LRW release was in the range of 30–90 d for routine releases and substantially longer for leaks from HLW tanks. It seems to be questionable to characterize by a single value of hold-up time the mixture of the released liquid wastes, given the different and non-specified technological histories most probably influenced by chemical separation and environmental transfer processes.

The materials relevant to the determination of the total activity and radionuclide composition of the radioactive releases into the Techa River in 1949–1951 recently published by Mokrov (2003a, 2003b) do not contain any new experimental data, but are based on a new analysis of the results presented by Alexandrov et al. (1951) on the radionuclide composition of the release water sample from 24–25 September 1951. Mokrov's analysis includes a number of weak points that are partly due to the paucity and low quality of the data:

1. the assumption that the release water sample of 24–25 September 1951 is representative of the long-term normal release of liquid wastes into the Techa River in 1949–1951 may not be entirely valid;
2. the radionuclide composition in the water sample may reflect a mixture of hold-up times and systematic errors could exist in the methods used for the evaluation of beta and gamma activities in the early 1950's;
3. the radiochemical separation into five groups of elements (strontium/barium, cesium, ruthenium, zirconium/niobium, and rare earth elements) and subsequent counting of the extracted materials using a Geiger-Müller counter does not allow for the determination of the hold-up time with a good sensitivity in the range from at least 10 to 120 d (see Table 5 in Mokrov 2003a); the $\beta/\gamma$ ratio of the mixture of the fission products also is relatively insensitive to the value of the hold-up time in the range from 20 to 200 d (see Fig. 3 in Mokrov 2003a);
4. the radionuclide group measurements were not corrected to account for the energy-dependent absorption of beta radiation in the end-window counter window material because of the lack of information on the radionuclide composition; and
5. the reference to a memoir monograph (Kruglov 1995) to justify a short hold-up time (about 35 d) cannot be considered as strong evidence.

Even if Mokrov's analysis is not entirely convincing, the array of arguments that it presents clearly points to a need to re-evaluate the reliability of the radionuclide release composition corresponding to the average age of fission products of 1 y that is used in TRDS-2000. A review of the estimate of the total activity released also would be desirable. Unfortunately, the records that documented the activity released into the Techa River during the early phase of operation (1949–1951) were destroyed. The remaining available information that is directly related to the releases is reportedly scarce and not accessible for external experts. The only information that is publicly available has been provided by the scientists from Mayak PA, allegedly on the basis of a few scientific reports. However, there are reportedly technical documents in the Mayak PA archives in which the operations of the plant had been recorded, and from which information on the releases (beta activity, radionuclide composition, chemical form) might be inferred.

It is important for Mayak PA staff to analyze these documents carefully, in order to extract information that is relevant to the estimation of the source term, and to make this information available in the first step to URCRM and, in a second step, to an especially established group of radiochemical experts so that it can be reviewed extensively. It is noted that the proposal for an International Science and Technology Center (ISTC) project of re-evaluation of the source term, which involves various Russian and American organizations, is a good step in the direction of a joint and careful analysis. The clarification of issues related to the determination of the source term would be facilitated substantially if the existing historical reports (draft doctoral thesis of D. Ilyin, 1956, and the report of "Alexandrov's Commission," 1951) were made available for the joint analysis.

In order to obtain additional information on the source term, it is also strongly recommended to contact and specifically interview members of the Mayak PA staff who were involved in, or familiar with, the operation of the radiochemical plant and of the waste-management facility during the early phase of operation (1949–1951).

Finally, it was suggested that it might be promising to explore whether there are any environmental samples (e.g., mussel shells, tree rings, etc.) that through mass spectrometry, etc., could provide direct evidence of the elemental composition of contaminants over time at various downstream points in the Techa River.

As a way forward, different possible proportions between normal discharges and unintended releases from high-level waste tanks should be considered based on existing historical records and further checked for consistency with the environmental monitoring data. Uncertainties in the radionuclide composition of the releases into the Techa River should be accounted for in the estimation of the radiation dose.

## ENVIRONMENTAL TRANSFER OF RADIONUCLIDES

### TRDS-2000 dosimetry system

The Techa River model was developed (Vorobiova and Degteva 1999) to describe the radionuclide transport in the free-flowing Techa River (7–237 km from the site of release). The purpose of this model was to fill the gaps existing in environmental monitoring data for the early period of 1949–1951. The processes taken into account in this model were dilution, advection, sorption, and radioactive decay. The following input data were used in the model:

- Source term as evaluated by Mayak PA experts (Ilyin 1956; Mokrov et al. 2000);
- Radionuclide specific soluble and suspended fractions of releases (Alexandrov et al. 1951). It was assumed that all solid particles suspended in the releases settled in up-ponds before reaching the Techa River; and
- Hydrological parameters such as distance-dependent flow rate, river velocity, channel and riverbed characteristics (Agapitova 1975; Marey 1959; Marey et al. 1965).

Model parameters were evaluated on the basis of data on radionuclide migration in artificial flowing reservoirs (Agafonov et al. 1960) and beta activity measured in Techa River water in 1951. The model validation vs. independent experimental data showed reasonable agreement of its predictions with the following data sets:

- distance dependence of $^{90}$Sr concentration in flood-plain soils;
- distance dependence of the maximum content of $^{90}$Sr in human bodies;
- distance dependence of $^{137}$Cs concentration in bottom sediments and flood-plain soils; and
- gross-beta activity in bottom sediments of the Techa River for 1951–1952.

### Recent findings

Recently, Mokrov has developed and published a more sophisticated model of aquatic transfer of radionuclides released in 1949–1951 from Mayak PA into the Techa River and its basin (Mokrov 2003b). This specific model, based on more general hydrological modeling (HEC-6 1993), explicitly accounts for sorption exchange of relevant radionuclides between liquid and solid (particles, bottom sediments) phases and for transport of solid particles with water flow. Mokrov also introduced in his model detailed hydrological characteristics of different river basin locations as collected in the 1950's and supplemented by assumptions for the later period, when the riverbed characteristics had changed. The predictions of the suggested model agree generally well with the available data on total beta and gamma activity of the Techa River bottom sediments, sampled in 1950–1951 at different distances from the release site, which are archived at Mayak PA and presented in detail by Mokrov (2003b). Mokrov suggests that the modified aquatic transport model for the Techa River and its basin can be readily used to estimate doses.

### Analysis

Two approaches to river modeling have been used to describe the transport of radionuclides along the Techa River and to evaluate the distribution of the activity among the liquid phase, the sediments on the shore, and the sediments on the riverbed. These models make use of the same sets of environmental measurements that were for the most part made in the year 1951 and in later years—that is, near the end or after the period of substantial releases. In order to improve the quality of the models, concerted actions of the authors of TRDS-2000 and Mayak PA experts are recommended aiming to:

- make sure that both river models are suitable for the purpose of dose reconstruction, especially for the period of major releases in 1950–1951;
- validate the two existing river models using the same sets of environmental data for the same locations and for the same time periods;
- on the basis of the results of the validation, identify the advantages and disadvantages of the two existing river models; and
- develop a single model, if feasible, in which the source term, the hydrological data, and the environmental radiation data are correlated as well as possible.

## EXTERNAL DOSE ESTIMATION

### TRDS-2000 dosimetry system

The basic data used in TRDS-2000 for the reconstruction of doses from external irradiation are as follows:

- Dose rates in air near the river shoreline, evaluated on the basis of (1) Techa River model calculations for the period 1950–1951; and (2) for 1952 and later, measurements performed by specialists of the Mayak PA, the Institute of Biophysics, and the URCRM;
- Mean ratios of dose rate in air near the river shore to dose rate in air in residence areas, evaluated on the basis of direct measurements performed by specialists of Mayak PA, the Institute of Biophysics (1951–1956), and the URCRM (1980–1983). River-to-residence dose-rate ratios were found to depend on shore topology, settlement location and distance from river shoreline, and to vary from 4 to 200 for the 40 Techa River settlements;
- Indoor-to-outdoor ratios of dose rates in air, evaluated on the basis of direct measurements performed by specialists of the Institute of Biophysics (1953–1955);
- A simplified model of typical life pattern, developed by Dr. Saurov of the Institute of Biophysics on the basis of interviews performed in the 1950's. The model results were compared with analogous studies conducted on the Techa River in 1993 and on the Tom River in the 1970's; and
- Age-dependent conversion factors from absorbed dose in air to absorbed dose in organs, taken from publications by Petoussi et al. (1991) and Eckerman and Ryman (1993).

Model assessments of beta activity in bottom sediments and calculated dose rates in air near the river shoreline for 1952 were compared with the measurements. The good agreement of calculated and measured values provides reasonable assurance that the model assumptions and calculations are correct, at least for 1952 onwards.

External red bone marrow doses calculated for permanent residents of Metlino and Muslyumovo villages show that there are large differences in external doses for those residents who lived close to the river and those who lived in residences far from the river (Table 2). The dose estimates presented in Table 2 seem to be in agreement with the information presented by Angelina Guskova at the meeting. Guskova indicated that cases of chronic radiation syndrome (CRS) had been diagnosed among the residents of the riverside settlements. In the first years of follow-up, CRS was diagnosed in 940 residents (Kossenko et al. 1994). After careful verification of CRS diagnosis based on long-term follow-up of the patients, it was recognized that the primary diagnosis had been justified for 66 individuals, of whom most individuals resided in Metlino and other villages on the

**Table 2.** Estimated red bone marrow doses from external irradiation for permanent residents of Metlino and Muslyumovo (Degteva et al. 2005).

| Residence relative to the Techa River | Absorbed doses (Gy)[a] | |
|---|---|---|
| | Metlino | Muslyumovo |
| Close residents | 1.24 (0.78–1.85) | 0.042 (0.023–0.071) |
| Distant residents | 0.35 (0.28–0.43) | 0.011 (0.009–0.013) |
| Average (TRDS-2000) | 0.42 (0.30–0.68) | 0.017 (0.010–0.039) |

[a] Mean values and 90% confidence intervals (in parentheses).

upper Techa River. Red bone marrow doses to these patients until the time of diagnosis were estimated to either exceed or to be close to 1 Gy.

Sensitivity analysis of the external doses indicates that one of the key parameters for external exposure is the river-to-residence dose-rate ratio. This means that the uncertainty in external doses could be improved with data on subjects' home addresses with individual locations within villages; the collection of such information has been a matter of recent investigation based upon copies of old tax books and other relevant information.

**Recent findings**

As presented in the section on the source term above, Mokrov recently suggested that both total activity and isotopic composition of the radionuclide release into the Techa River in 1949–1951 were substantially different from the previous Mayak PA results used in the existing TRDS-2000, among other things, for the external dose estimation. If this suggestion is confirmed, it would have direct and immediate influence on the external dose estimations based both on the source term and modeling of the released radionuclide transport in the aquatic environment.

According to Mokrov's preliminary estimates, radiation conditions and associated human external doses received in 1949–1951 were predominantly determined by gamma radiation of the relatively short-lived radionuclides $^{95}Zr/^{95}Nb$, $^{140}Ba/^{140}La$, $^{103}Ru/^{103m}Rh$ and some others with minor contribution of $^{137}Cs/^{137m}Ba$. The external dose estimates to the Techa River basin residents would be substantially higher than those presented in TRDS-2000. In his calculations of external dose, Mokrov assumed a semi-infinite thin plane source geometry.

It is suggested that external dose to skin due to close contact with clothes and bed linen contaminated with beta emitting radionuclides from river water used for washing had been quite substantial and should be accounted for in the health effects studies.

**Analysis**

Doses from external irradiation developed in TRDS-2000 are based on measurements and modeling of exposure rates, associated with residential histories obtained through tax books and interviews. The cumulative exposure at Metlino was validated with the measurements of thermoluminescence (TL) using brick samples from a mill located in this village (Jacob et al. 2003). Modeling of dose ratios in brick walls and in open areas visited by local inhabitants was questioned by Mokrov who raised concerns caused by major changes in the river geometry during the period of higher dose rates.

Electron paramagnetic resonance (EPR) measurements on teeth also have been shown by Tolstykh et al. (2003) to have the potential to provide estimates of external doses received by residents along the Techa River, even in the presence of substantial $^{90}Sr$ concentrations in teeth.**

Continued efforts to validate the developed TRDS-2000 system of external dose reconstruction with modern measurements of accumulated dose in environmental samples and human tissues would reduce uncertainties. In particular, it is recommended to continue the analysis of:

- TL in bricks, if suitable bricks can be found;
- EPR in teeth, assuming that the separation of the internal dose from $^{90}Sr$ and the external dose from environmental gamma-radiation can be achieved reliably; and
- FISH in blood samples, assuming that methodological issues regarding blood lymphocytes and especially the influence of the internal dose from $^{90}Sr$ can be solved.

In order to provide the epidemiologists with person-specific dose estimates, it is recommended to modify TRDS-2000 in order to supplement the locality-average estimations of external doses with individualized ones based both on local radiation conditions and human behavior data. It is important to estimate the contributions of the occupancy in different locations, e.g., the river and its floodplain, locality outdoor, locality indoor, etc., to the external dose of the Techa River basin residents.

The external doses calculated according to Mokrov's methodology are of a preliminary nature. They depend primarily on the source term specification and are far from being as extensive as those presented in TRDS-2000. Mokrov's calculations are based on an oversimplified geometry of an infinite plane thin source with uniform radionuclide surface density, which substantially overestimates the dose rate in air. It will be necessary to revisit Mokrov's methodology and results, especially if the future assessment of the total activity and isotopic composition of the radionuclide release into the Techa River in 1949–1951 concludes that the source term should be changed for dose reconstruction purposes.

** In a draft publication that was provided at the Workshop in Moscow, Degteva et al. (2005) indicate that the validation of the cumulative dose to individuals based on EPR measurements on tooth samples, and FISH (fluorescence in-situ hybridization) measurements on blood samples was generally consistent with results of other assays, including thermoluminescent measurements of quartz extracted from bricks taken from old buildings. Results were also consistent with those estimated with the TRDS-2000. However, more validation work is considered essential to the credibility of the dose calculations being made with the TRDS-2000.

## INTERNAL DOSE ESTIMATION

### TRDS-2000 dosimetry system

The basic data used in TRDS-2000 for the reconstruction of doses from internal irradiation are as follows:

- results of about 30,000 measurements of $^{90}Sr$ in tooth tissue, performed from 1959 through 1995, using a tooth-beta counter (TBC);
- results of about 38,000 measurements of $^{90}Sr$ and $^{137}Cs$ in people, performed from 1974 to 1998, using a whole-body counter (WBC);
- age-dependent annual radionuclide intakes in different settlements, reconstructed on the basis of the radionuclide measurements in human body and tissues ($^{90}Sr$ and $^{137}Cs$) indicated above, radionuclide measurements of environmental samples and local foodstuffs, and, for short-lived radionuclides, estimates based upon the historical release information and Techa River model;
- age-dependent biokinetic and dosimetric models for $^{90}Sr$ and $^{137}Cs$; and
- individual residence history (date of residence in Techa River villages) according to URCRM database "Man" for all members of the ETRC and TROC.

The most important problem of internal dose calculation is the assessment of the radionuclide intake. The data used for this purpose differ depending on the radionuclides that are considered. The source-term data have not been used for the reconstruction of the intakes of the long-lived radionuclides $^{90}Sr$ and $^{137}Cs$, but they are crucially important for the estimation of the intakes of short-lived radionuclides.

**$^{90}$Sr intake reconstruction.** According to present knowledge on radionuclide release, $^{90}Sr$ is the main contributor to the dose for the residents along the Techa River. The reconstruction of the $^{90}Sr$ intake is based on experimental data only, and the $^{90}Sr$ intakes were used as a basis (reference intake) for other radionuclides. Reconstruction of $^{90}Sr$ intake was initially performed for the reference settlement Muslyumovo using the following data sets on $^{90}Sr$ measurements: (1) data on tooth-beta-counter (TBC) measurements for the reconstruction of dynamics of the intake in 1950–1956 and (2) whole-body-counter (WBC) data and measurements of $^{90}Sr$ contents in foodstuffs and river water (URCRM data base ENVIRONMENT) for the derivation of absolute values of $^{90}Sr$ intake. It is clearly shown in Table 3 that drinking water was the main pathway of internal exposure from $^{90}Sr$.

The calculation of $^{90}Sr$ intakes in settlements other than Muslyumovo is also based on WBC measurements of Techa River basin residents. According to WBC data, the *average* value of the settlement-specific $^{90}Sr$ intake does not strongly depend on the distance from the site of releases and, therefore, on the concentration of $^{90}Sr$ in river water. This feature should be considered for radionuclides other than $^{90}Sr$ because drinking water was by far the predominant source of diet contamination in 1950–1952. Therefore, it is impossible to assess the real pattern of intake on the basis of only environmental data or/and model calculations.

**Table 3.** Contribution of dietary components to the daily intake of $^{90}Sr$ by ingestion for adult Muslyumovo residents in 1950–1951 (TRDS-2000).

| Dietary component[a] | Daily consumption (kg) | $^{90}Sr$ concentration[a] (relative to river water) | Contribution to intake of $^{90}Sr$ by ingestion (%) |
|---|---|---|---|
| Drinking water[b] | 1.0–1.6 | 1 | 92–96 |
| Milk and milk products | 0.5–0.6 | 0.04–0.1 | 2.0–3.5 |
| Meat | 0.075–0.1 | 0.05–0.1 | |
| Fish | 0.02–0.03 | 1–2 | 2.0–4.5 |
| Vegetables | 0.2–0.4 | 0.002–0.004 | |

[a] Data on diet composition and transfer coefficients from river water to foodstuffs were taken from IBPh and URCRM Technical Reports. Grain products were not contaminated because grain products were not cultivated in the floodplain.

[b] In 1950–1951, the supply of drinking water in Muslyumovo was provided by 2 wells for about 4% of the residents and by the water from the Techa River for the other 96%.

**$^{137}$Cs and short-lived radionuclides.** As mentioned above, source-term data have not been explicitly used for the reconstruction of $^{137}Cs$ intake. The primary data used are the measured and modeled concentration ratios between $^{137}Cs$ and $^{90}Sr$ in river water. Thus, environmental data and calculations made with the Techa River model form the basis for the reconstruction of $^{137}Cs$ intake.

The estimation of intakes of short-lived radionuclides is also based on calculations with use of the Techa River model. For short-lived radionuclides only the concentration ratios in releases were used for intake reconstruction. However, data sets on measurements of total-beta activity in excreta of Metlino residents (measurements from 1951) permit verification of radionuclide-intake levels. This approach permits a rough estimation of the intakes of short-lived radionuclides based on ICRP metabolic models for non-strontium radionuclides.

**Internal doses and dose uncertainties.** Individual estimates of internal dose, taking into account individual data on Techa residents, were calculated for all members of the ETRC. Results are shown in Table 4.

**For an identified release composition, the main factors influencing values of internal doses are:**

- Period of residence in settlements along the Techa River;

**Table 4.** Distribution of internal dose accumulated through 1990 for about 30,000 members of the ETRC (Degteva et al. 2006). The upper table gives the dose estimates for several population percentiles. The lower table gives the percentage of the population within several dose intervals.

| Organ or tissue | Dose estimates (Gy) for the population percentile | | | |
|---|---|---|---|---|
| | 10% | 50% | 90% | Maximum |
| Red bone marrow | 0.004 | 0.21 | 0.71 | 2.0 |
| Lower large intestinal wall | 0.001 | 0.08 | 0.38 | 1.1 |
| Stomach wall | 0.0009 | 0.006 | 0.051 | 0.5 |
| Uterus | 0.0008 | 0.005 | 0.046 | 0.4 |

| Organ or tissue | % of population within the dose intervals | | | | |
|---|---|---|---|---|---|
| | ≤0.001 Gy | 0.001–0.01 Gy | 0.01–0.1 Gy | 0.1–1 Gy | >1 Gy |
| Red bone marrow | 4.1 | 10.4 | 13.4 | 68.9 | 3.2 |
| Lower large intestinal wall | 7.7 | 9.1 | 40.4 | 42.7 | 0.1 |
| Stomach wall | 11.1 | 57.8 | 23.5 | 7.6 | 0 |
| Uterus | 12.1 | 60.4 | 20.0 | 7.5 | 0 |

- Sources of water supply in the settlements;
- Distance downstream from the site of release; and
- Age at the time of major intakes (1950–1952). The role of this factor can be explained by the age dependence of strontium and calcium metabolism.

The combination of these factors resulted in a high variability of individual internal doses among the members of ETRC; the determination of the source of water supply in specific settlements was identified as the major contributor to dose uncertainties. For villages with Techa River as a major source of drinking water, the ratio of the 97.5$^{th}$ percentile to the 2.5$^{th}$ percentile can be as high as 20 to 30. For villages with mixed sources of drinking water (river and well), the range can extend over two orders of magnitude. However, according to preliminary assessments, the future use of data on individual $^{90}$Sr-body/tissue measurements can result in a significant reduction of uncertainty in individual estimates of internal dose.

## Recent findings

As presented in the section on source term above, Mokrov recently suggested that the source term of the radionuclide release into Techa River in 1949–1951 was substantially different from the previous Mayak PA data used in the existing TRDS-2000, among other things, for the internal dose estimation. If this suggestion is confirmed, it would have a direct influence on the internal dose estimations, especially for short-lived radionuclides, based both on the source term and modeling of the released radionuclide transport in the aquatic environment.

According to Mokrov's preliminary estimates, environmental contamination of drinking water and associated human internal doses received in 1949–1951 were predominantly determined by the following radionuclides: $^{90}$Sr/$^{90}$Y, $^{89}$Sr, $^{140}$Ba/$^{140}$La, $^{131}$I, and some others. The dose estimates for red bone marrow caused by beta radiation of $^{90}$Sr/$^{90}$Y do not differ significantly from TRDS-2000 data. However, doses from $^{89}$Sr would be higher than those estimated by TRDS-2000 by at least an order of magnitude and would possibly exceed those from $^{90}$Sr/$^{90}$Y. Additional attention should be paid to whole body internal dose from ingestion of a number of short-lived radionuclides and specifically to thyroid doses caused by $^{131}$I. In total, the internal dose estimates to the Techa River basin residents would be much higher (by a factor of 2 to 3) than the estimates presented in TRDS-2000 (Mokrov 2003b, 2004).

## Analysis

The TRDS-2000 doses from internal irradiation with long-lived radionuclides $^{90}$Sr/$^{90}$Y and $^{137}$Cs/$^{137m}$Ba are mainly based on numerous measurements of $^{90}$Sr in teeth and bones. Because the doses from short-lived radionuclides could not be adequately validated using standard techniques, they were estimated based on the release radionuclide composition and associated aquatic transfer modeling.

It is recommended to investigate the possibility of making measurements of stable or of long-lived isotopes of the short-lived radionuclides to infer the dose from those short-lived radionuclides. In the case that it is found that the contribution to the internal dose from intake of $^{95}$Zr/$^{95}$Nb is substantial, improvements of the metabolic models for these elements for the environmental conditions of interest would be desirable, because the existing ICRP metabolic models might not be reliable enough for dose reconstruction purposes.

In order to provide epidemiological studies with mostly required person-specific dosimetric data, it is recommended to modify TRDS-2000 in a way to supplement the locality-average estimations of internal doses with individualized ones based both on local environmental contamination and individual human consumption data. It is important to define and present contributions of drinking water and different foodstuffs to internal dose of the Techa River basin residents.

The internal doses calculated according to Mokrov's methodology depend in the first place on the source term specification. It is recommended to revisit his internal dose calculations if further assessment of the total activity and isotopic composition of the radionuclide release into Techa River in 1949–1951 concludes that the source term should be changed for dose reconstruction purposes.

## GENERAL CONCLUSIONS AND RECOMMENDATIONS

- Very large amounts of radioactive materials were released into the Techa River during the early years of operation of the Mayak complex, in particular between March 1950 and November 1951. These releases led to substantial doses to the residents near the Techa River, and, subsequently, to health effects. Numerous studies have been conducted or undertaken on the risk estimates. These studies need to be based on reliable estimates of individual dose.
- The Techa River Dosimetry System TRDS-2000 provides dose estimates for all of the population groups that resided along the Techa River (Degteva et al. 2000a, 2000b). It is based on a large number of environmental and human data, on a river model that was validated using measured data sets, and on a careful assessment of the lifestyle habits of the population groups that are considered. While the methodology of TRDS-2000 is basically sound, *pending the resolution of the issues set out below* and further investigations of exposure of the Techa River population from other sources (e.g., medical examinations, other releases from the Mayak complex), *the results of epidemiological studies making use of TRDS-2000 should be qualified as preliminary,*
- On the basis of the analysis of a specific dataset (measurements of the radionuclide distribution in an effluent sample) and of access to some information that is not widely available, it has been suggested by a scientist from Mayak PA, Yuri Mokrov (2002a, 2002b, 2003a, 2003b, 2003c), that the source term published earlier by Mayak experts may be in error, so that the contribution to the total release of short-lived radionuclides with half-lives of a few weeks to a few months to the radionuclide releases into the Techa River in 1949–1951 would have been much greater than previously estimated. Because of the short half-lives of those radionuclides, their presence in the environment and in humans cannot be detected directly by means of current measurements. In addition, it does not seem that environmental measurements of short-lived radionuclides were made at the time when large releases occurred. Therefore, the doses from short-lived radionuclides have to be based, to a very large extent, on the estimates of the activities that were released.
- The conclusions reached by Mokrov (2002b, 2003a, 2003c) are based on different interpretations by him and in TRDS-2000 of limited data sets related to the activities released, which appear to be discrepant. Although reservations about the validity of Mokrov's claims were made during the workshop, it was not possible to obtain a consensus of opinion during the time allotted to the meeting. It was recognized that efforts to re-evaluate the radionuclide composition of the liquid releases are crucially important, and that they should make use of all available information on historical monitoring data and on the procedures used in the plant.
- Unfortunately, as long as the information on which the suggestion to substantially change the source term is based remains unavailable to most of the scientists, it is impossible for the international scientific community to make a sound evaluation. It is important that Mayak PA experts: (1) declassify and release historical technical documents that might be used for the purposes of dose reconstruction as soon as possible; (2) to the extent possible, share this information with URCRM and other interested organizations; and (3) co-operate fully with URCRM to develop a methodology of dose reconstruction that is accepted without reservation by the scientific community. The establishment of a special panel with expertise in reprocessing, radiochemistry and the management of waste streams, in order to revisit the source term would promote clarification of this crucial issue.
- In order to implement the previous recommendation, a feasibility study with Mayak PA experts as principal investigators should be undertaken, with the participation of URCRM scientists as well as experts from the U.S. and Europe. The objective of the feasibility study would be an evaluation of all available data and information that might be used for the purposes of dose reconstruction for the Techa River population. Within its framework, the procedures for data access might be developed in the same manner as in the research program developed under the auspices of JCCRER, in order to make the relevant information open to all interested organizations. Such a management process would ensure the wide acceptance of the study results by the scientific community.
- In order to improve the quality of the models used for simulation of aquatic transport of radionuclides along the Techa River, concerted actions of the authors of TRDS-2000 and Mayak PA experts are recommended aiming to validate the two existing river models against environmental data and identify their advantages and disadvantages; and, if it is found possible, to develop a single model for the purpose of human dose

reconstruction. Involvement in this work of impartial experts in modeling radionuclide transfer in freshwater bodies would be very advisable.
- All the human dose estimates should be associated with an assessment of their uncertainties, especially those that can lead to a bias. Remaining uncertainties of the release radionuclide composition should be accounted for in the dose uncertainty analysis.
- In order to reduce dose uncertainties, the efforts aiming to validate external doses reconstructed by means of TRDS-2000 with modern measurements of accumulated dose in environmental samples and human tissues should be extended. The most suitable modern experimental methods seem to be thermoluminescence measurements in bricks, electron paramagnetic resonance in teeth, and fluorescence in-situ hybridization in blood samples.
- Individual doses, and not only group doses, should be estimated. This means that all individual $^{90}$Sr measurements should be used and that personal information should be obtained and applied on the location of the residence in the settlement, source of drinking water, etc., through interviews or questionnaires administered to the cohort members or to their relatives.
- In order to obtain more complete information on the doses received by the Techa River basin residents, the following sources of exposure should be accounted for, on a group or individual basis, as appropriate: the airborne emissions from the Mayak PA stacks (primarily $^{131}$I and rare gases); the airborne radionuclide emissions from the 1957 explosion; the resuspension of radioactive aerosols from Lake Karachay in 1967; and the intense medical radiological surveillance.
- It is stressed that the explicit participation of Mayak scientists is crucially important for the project of dose reconstruction to be successful. Several years may be needed to accomplish this task. Also, given the importance of the project, periodic peer review of its progress by an international group of experts is recommended.

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